# GelMan Thoracic Surrogate for Underwater Threat Neutralization

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## LONG-TERM GOALS

Hostile underwater swimmers are a potential threat against military and commercial shipping anchored in civilian, military or dual-use ports and harbors. Conventional defensive methods to quickly disable or defeat such a threat may pose a risk of injury or death to non-hostile individuals on vessels engaging in routine activities in the same area. An alternative concept is to add an Underwater Threat Neutralization (UTN) system, based on directed low frequency underwater ensonification for swimmer detection and tracking. The goal of this work is to develop an instrumented human surrogate technology to demonstrate how acoustic energy at specific frequencies, sound pressure levels and time durations would be predicted to affect hostile swimmers at various depths and orientations, since the demonstration and validation of such a system on human test subjects is not ethically possible.

## OBJECTIVES

The objectives of this effort are to develop and demonstrate an NRL GelMan thoracic surrogate for use in an underwater environment and quantify sensitivity of lung resonant response frequencies to external water pressure. The key objectives for FY07 were (i) to complete the GelMan-Underwater design, (ii) validate the design in tank testing, (iii) fabricate a GelMan-Underwater device with surrogate lungs capable of assessing internal dynamic response to external sound sources, (iv) measure the sound source performance at sound pressure levels relevant to prior human response testing documented in the literature, and (v) analyze and compile test data as a reference for the other

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**Hostile underwater swimmers are a potential threat against military and commercial shipping anchored in civilian, military or dual-use ports and harbors. Conventional defensive methods to quickly disable or defeat such a threat may pose a risk of injury or death to non-hostile individuals on vessels engaging in routine activities in the same area. An alternative concept is to add an Underwater Threat Neutralization (UTN) system, based on directed low frequency underwater ensonification for swimmer detection and tracking. The goal of this work is to develop an instrumented human surrogate technology to demonstrate how acoustic energy at specific frequencies, sound pressure levels and time durations would be predicted to affect hostile swimmers at various depths and orientations, since the demonstration and validation of such a system on human test subjects is not ethically possible.**

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elements and testing of the UTN harbor security system. These FY07 objectives and technical plan are based on the results of the FY06 effort and the current UTN program objectives for harbor security.

## APPROACH

The fundamental approach in this effort is to develop an appropriate NRL GelMan-Underwater surrogate human measurement device, based upon surrogate tissue properties and relevant anatomy, to provide quantitative measurement representative of submerged human responses to the continuous acoustic energy at frequencies and intensities consistent with neutralization. Such a device would allow assessment of a UTN system sound source's ability to affect sensitive internal organs, such as the lungs. This data would be used in conjunction with existing data on acoustic frequencies and discomfort threshold sound pressure levels to compile source frequency, external sound pressure level (at a known distance from the source), and source time duration that are projected to disable or defeat a hostile swimmer. The device would provide essential information for UTN system design, calibration and validation. The key features of such a device are the anatomical details of relevant organs, use of materials that simulate human tissues, and its dynamic fidelity simulating that of the human thorax. The steps within the approach consisted of (i) concept designs with integration into ONR UTN requirements, (ii) device fabrication and testing procedures, and (iii) instrumentation and control software.

## WORK COMPLETED

The major thrusts in FY07 were to complete the GelMan-Underwater surrogate design, fabricate a surrogate for testing, validate its operation underwater at depth in tank, and measure the effects of a sound source on the surrogate lungs so that the surrogate could be used to measure the effects of UTN sound sources.

*Design and Simulation* - The performance of the FY06 prototype surrogate was reviewed and the revisions to the design were formulated to address issues identified during the prior year testing. Design objectives for the GelMan-Underwater surrogate in FY07 included revising the pressure and accelerometer sensor suite for additional sensitivity and water resistance. The sensor suite included ten pressure sensors (10 channels) and 6 tri-axial accelerometers (18 channels). One set of sensors was placed at the front, middle and back of each lung. Four pressure sensors were placed externally on the surrogate. The ability to suspend the GelMan in both vertical and horizontal orientations was a priority.

*Materials and Component Development* - Tissue simulant materials were developed to meet the needs of any additional interest in abdominal organs (liver, stomach, large intestine, small intestine) and structures (trachea) featuring mechanical and acoustic property fidelity. Discussions with the University of Texas Applied Research Laboratory (UTX-ARL) on NRL lung properties and real lung tissue properties are in progress for use in UTX-ARL lung models.

*Device Fabrication* - New organ molds for heart and lungs were fabricated to replace worn out molds. Work was initiated on new liver and stomach molds to add these to anatomy. Intestines can be fabricated as needed using solid and/or hollow cylindrical forms.

Lucas Industries was identified as a vendor to fabricate a full torso mold with headform to allow additional organs as needed. These features would provide additional physical and geometric fidelity, and larger acoustic signature profile. Two molds were ordered, and a mannequin form was provided to

the vendor in mid-FY07 from which to base fabrication**.** Estimated delivery was 8 weeks. In spite of delays in fabrication and delivery due to the vendor's move to new production facility, the molds were received at the end of FY07.

*Dragon Skin* - A new commercial product (a two-part silicon system) was identified to upgrade the external coating applied to the surrogate as waterproofing and as a surrogate skin. While no evidence of significant water infiltration was found upon disassembly of the FY06 surrogate prototype, this product provided improved waterproofing, mechanical properties, resilience and ease of application for the FY07 surrogate.

*Sensor Suite* - Upgrades were made (i) to resist water infiltration into accelerometer and pressure sensor cables, (ii) and to increase sensitivities by a factor of 20 and 2 respectively for the underwater acoustics. The use of 15 meter (50 ft.) integral cables for both accelerometers and pressure sensors eliminated any submerged connectors. Accelerometers previously shipped were not optimal in size and mass, but were acceptable for the underwater testing conducted. The vendor is replacing these sensors with the correct ones for future testing.

*Software and Hardware* – NI LabView VI modules were written to meet the unique testing requirements of this program. The software generated 80 sec long log sweeps from 20 – 320 Hz or 160 msec weighted linear chirps from 20 – 320 Hz from the NI Pixie system. These signals were generated synchronously with data collection to provide "on-the-fly" averaging for improving signal-to-noise ratio and the processing multiple data sets while eliminating the need to store large data sets. Software was used to reject spurious false triggers, which occurred at a 0-10% rate of the true triggers.

*Standard Length GelMan-Underwater Torso* – The device was fabricated for underwater testing using the materials and sensors as described. Modal tests in air were conducted with an impact hammer, a standard practice for impact reference points located on torso and to validate the dynamic response of the sensors in the surrogate model.

*Testing Procedures* - The NRL Acoustics Division tank, Penn state quarry and Naval Underwater Warfare Center / Newport RI Coddington Cove harbor were considered as test venues. The NRL acoustics tank was selected based on the late delivery of GelMan-Underwater components required for surrogate fabrication and discussion with Dr. Robert Headrick (ONR). Other factors included, environmental restrictions that limited the use of a low frequency 160dB sound source at Coddington Cove, and the availability of the required sound source prototypes at either location.

*NRL Acoustics Division Tank* – USRD type J13-1 sound projector delivered a greater than anticipated 153dB omni directional sound pressure level over a frequency range of 20 – 320 Hz in a tank 16.7 m (54.8 ft.) in diameter and 15.3 m (50.1 ft.) deep in the NRL tank. The tank interior wall and base surface are lined with sound absorbing materials for frequencies greater than 1KHz and the reduction of reflected sound by 1-10% for frequencies less than 1Khz. Based on previous and current tests, it was determined that resonant frequencies of the tank dominated the frequency spectrum. However, useful data was obtained in spite of sidewall and bottom reflections. Although not desirable, these characteristic may or may not exist in the quarry or in the harbor.

*NRL Team* – Additional members for the effort are; NRL - Andrew Geltmacher, Ed Gorkowski, Mike Saniga, Richard Everett and Amit Bagchi; and Honeywell - Dave Horner, Dirk Van Der Loo, and John Gauvin.

## RESULTS

In FY07 the underwater testing included data collection, processing and interpretation of sound effects on GelMan surrogate lungs at a depth of 7.62 m (25 ft.) and 0º to 360º orientation with respect to sound source. The FY06 water infiltration problems were resolved by using thinner and longer (15.24 m or 50 ft.) coaxial cables, with no cable connections underwater. Also for FY07, a more efficient sound projector produced higher sound pressure levels at the desired frequencies. However, we had some sensor reliability issues with the loss of one of the tri-axial accelerometer channels after initial set-up and prior to immersion of the surrogate model in the water, and only one additional channel was lost during testing. Thus, we were able to collect data from 26 of 28 channels.

The GelMan surrogate was deployed in the NRL Acoustic Division underwater acoustic tank with a USRD J13-1 sound source and National Instruments data acquisition system controlled by its internal processor and a laptop. The surrogate was placed at a depth of 7.62 m (25 ft.), and at a horizontal distance of 3.92 m (12.86ft) from the sound source with both vertical heads-up and horizontal chest down "swimming" position being tested. Prior to and after testing GelMan-underwater, reference measurements were taken with sound projector (USRD J13-1) and receivers (PCB 138M184 and Reson TC4013) separated by a distance of 3.92 m (12.86 ft.) This reference baseline sound pressure levels were averaged to reduce signal to noise ratios for both 80 sec. log-sweeps and the 120 msec weighted linear-chirps from 20-320Hz. Important note; in FY06, unusual resonance modes in the frequency domain were visible and unidentifiable, however in FY07, these resonance modes identified and confirmed as originating from the acoustic tank.

The GelMan surrogate was rotated about a vertical axis from 0º -360º through a series of 45-degree increments relative to the sound source to test the response relative to the source for both the vertical (heads-up) and horizontal chest down (“swimming”) position. Horizontal accelerations inside the surrogate changed with GelMan orientation. The large accelerations were associated with the sensor(s) being closer to and in line with the sound source, indicating that the acceleration decreased with sound penetration depth.

Lung resonance data from “Measurement of the depth-dependent resonance of water-loaded human lungs” by J.S. Martin, P.H. Rogers and E. Cudahy shows an $f_0$ resonance at atmospheric pressure to be 31.7 Hz. GelMan-underwater model-1 (FY06) showed a pressure resonance of 31.4 Hz from modal hammer impact in air. For GelMan-underwater model-2 (FY07), we measured in air, pressure resonance of 28.6 Hz for the external left front of lung and 22.9 Hz for the internal and the back of lung. Acceleration resonances for the front and internal Z-axis accelerometer for the left lung were measured to be 31.5 Hz and 36.2 Hz for back lung accelerometer.

With chirp excitation, the right front lung accelerometer showed slightly higher peak amplitude than right internal and right back of lung accelerometers with peak amplitudes of about 0.023m/sec$^2$. However in the Fourier domain there is significant difference in the frequency response for front, internal and back of lung accelerometers. For the front tri-axial accelerometer, three dominant resonant peaks at 80Hz, 118 Hz and 160 Hz are approximately equal in amplitude. At the center of the lung, the resonant peak amplitude at 120 Hz is approximately twice the peaks at 80Hz and 160 Hz. At the back of the lung, the peak frequency at 118 Hz increased by a factor of four above the other two resonant peaks.

Pressure sensors located in front of, inside and behind lungs showed no variation in peak amplitudes as a function of location between 20 and 320Hz. However, as a function of angular rotation (0º – 360º) about the vertical X-axis, all peak amplitudes decreased and increased proportionally by the same amount. Unlike the accelerations, the right-lung front pressure response did not vary noticeably for any angular position.

As a function of rotation from 0º – 360º about the vertical X-axis (is referenced pointing toward the neck), the Z-axis (is referenced pointing out from the sternum) acceleration showed a noticeable variation at 118 Hz (in Fourier domain) than the X-axis (an expected result. Because of Y-axis (is referenced pointing toward the shoulder) accelerometer malfunctions, no data was collected after rotating for 90º; however, the variations are expected to be similar to that for Z-axis.

When comparing the Z-axis acceleration for the internal right lung for both the160 msec. weighted linear chirp and the 80 second log-sweep of same amplitude and 0º rotation, the log-sweep produced higher amplitude by a factor of 16.6 at the corresponding peak frequency at 118 Hz.

When comparing the vertical and the horizontal orientation at zero degree, there is a time shift in maximum amplitude for the right lung Z-axis accelerometer. In the time domain, this starts at 52 seconds with a drop in amplitude at 42 seconds from vertical to horizontal. These peaks correspond to 118 Hz and 82 Hz respectively in the time domain of the logarithmic sweep. This suggests that the desired and effective frequency range for diver deterrence in the vertical and horizontal positions is between 82 – 118 Hz for maximum amplitude acceleration.

There are 300 million alveoli in human lungs. The alveolus radius is on the order of 100 microns with a wall thickness of 0.2 microns. The measured surrogate lung displacements in the vertical orientation were from 1.25-739.0 microns, suggesting that the UTN sound source pressure level objectives would produce internal lung motions larger than the wall thickness and on the same scale as the alveolus radius. The geometric structure of an alveoli cluster would be subjected to heterogeneous deformations and associated local strain amplifications and concentrations based on these results, which support the strategy of a lung mechanism for UTN system effectiveness on hostile swimmers.

Future efforts should address issues associated with open water environments. *First*, testing should best be conducted after acoustic characterization of any tank, quarry or harbor environment is mapped in order to understand the pressure field for different sound source and surrogate locations. *Second*, wave induced motions can influence the accelerometer measurements. The NRL tank tests showed vertical motion of bridge structure (caused by people walking on the bridge), from which the GelMan surrogate was suspended, could cause significant motion in the vertical direction of all accelerometers. This suggests that the surrogate should be tethered to bottom, or surface wave motion compensated or suppressed. *Third*, the GelMan surrogate response should be characterized at multiple depths. *Finally*, swimmer clothing such as fabric layers or a wet suit may also deserve consideration.

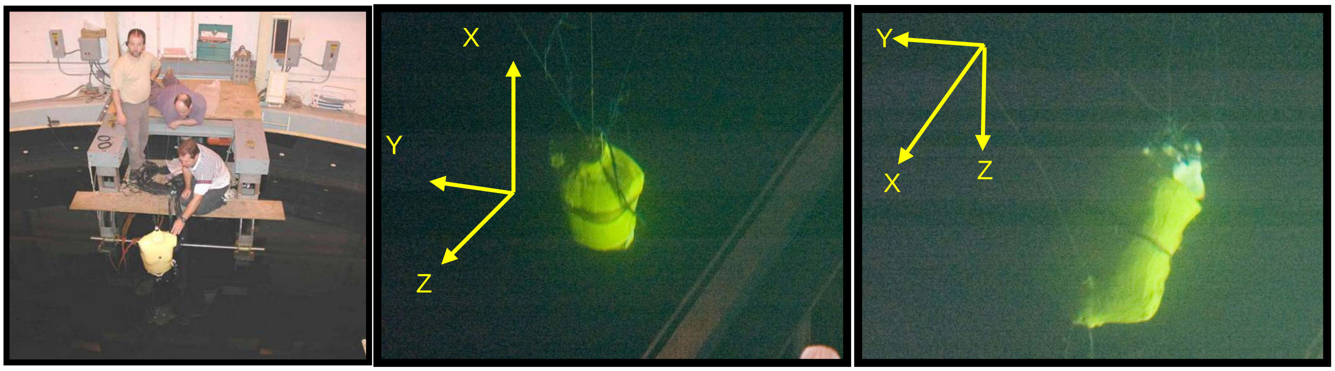
## IMPACT/APPLICATION

Based on the FY07 NRL Acoustic Tank results, the GelMan-Underwater human surrogate device is a deployable to meet the needs of the UTN program to measure sound source effectiveness in terms of surrogate lung tissue response in the torso geometry. Baseline test procedures, data acquisition and signal analysis methods have been developed for an acoustically challenging tank environment which qualitatively exhibits some of the same issues anticipated in harbor environments for low frequency /

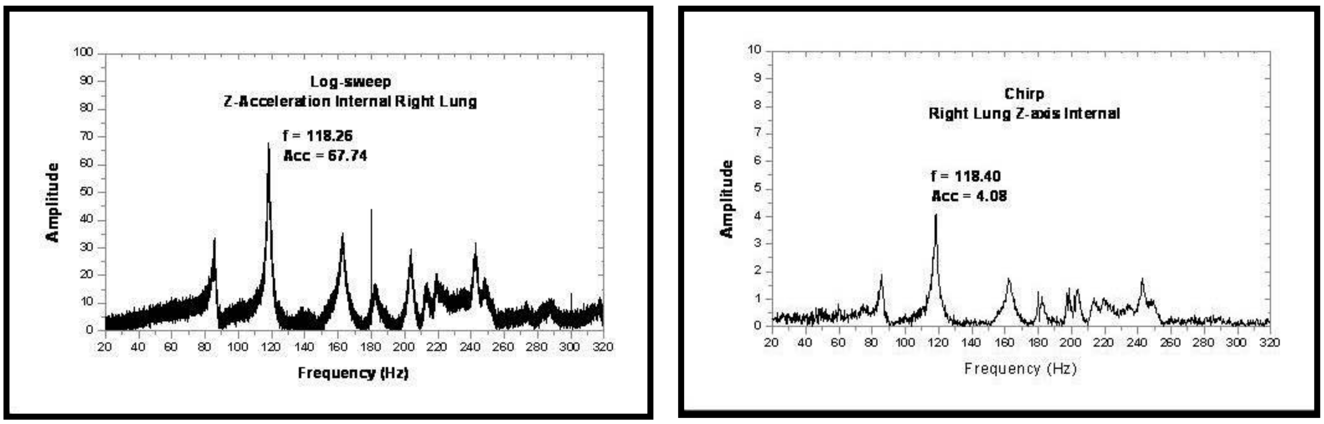
long wavelength sound sources. Test procedures for quarry or harbor testing should be developed based on these procedures with higher sound pressure levels

The GelMan-Underwater surrogate demonstrated the ability to measure differences in lung responses as a (i) function of sound source orientation from 0º – 360º around the surrogate, and (ii) function of vertical versus horizontal surrogate position in the water at depth. Measured internal pressures showed amplitude changes at all ensonification frequencies, although these changes are not uniform, the dynamic charactieristics of the human body and the GelMan surrogate are evident.

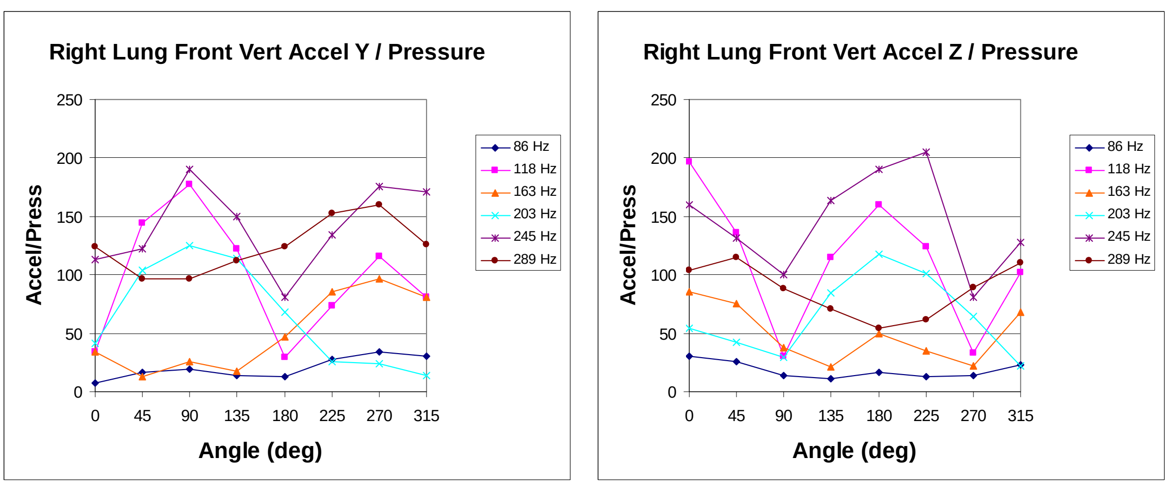
Based on the GelMan performance and measurements to date, the ability to execute log sweeps is recommended over weighted linear chirp sweeps. Measurements show log sweeps produce higher amplitudes internal dynamic displacements on the natural scale of the lung alveoli structures.




*GelMan-Underwater submerged at 7.62 m (25 ft.) in vertical and horizontal position.*




*Figures show internal right Lung Z-acceleration response for a Log-sweep (80sec duration) greater than Linear-sweep Chirp (160msec duration) for the same output drive current. Fourier spectrum plots also shows tank resonant peaks occurring at the same frequencies.*




*Ratio of peak-acceleration and pressure at corresponding frequencies (in the Fourier domain), for right lung as a function of GelMan-Underwater rotation about the vertical axis.*